NREL
Hydrogen Sensor Testing Laboratory

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DOE Hydrogen and Fuel Cells Program
2020 Annual Merit Review and Peer Evaluation
Meeting May 19 - 21, 2020

Project ID # SCS 021

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Overview

Timeline

- Project start date: 10/01/2010

Project continuation and direction determined annually by DOE

Budget

- FY19 DOE funding # :

  $ 534 K (35% for 2 subcontracts)

- FY20 planned DOE funding * :

  $ 475 K (3 tasks and 1 subcontract)
  - Hydrogen Wide Area Monitor (55%)
  - Sensor Placement with subcontract (25%)
  - Sensor Performance and Evaluation (20%)

- Total DOE funds received to date:

  $ 3,565 K

Since 2010, the NREL Sensor Testing Laboratory was under the NREL SCS AOP. A separate AOP for the NREL Sensor Laboratory was established in FY19 .

* In FY20 sensor testing was integrated into the Hydrogen Safety Research and Development (HSR&D) AOP.

Barriers

C. Safety is not always treated as a continuous process

F. Enabling national and international markets requires consistent RCS

G. Insufficient technical data to revise standards

Partners

Industry/Private: Element One, KWJ, First Element, Shell North America, AVT and Associates, CGA/Chart, Plug Power, Toyota North America

Government labs and agencies: LLNL, HSE/HSL, DOT/Transport Canada / ECCC

Academic: University of Maryland

Relevance
Need for Continued RD&D

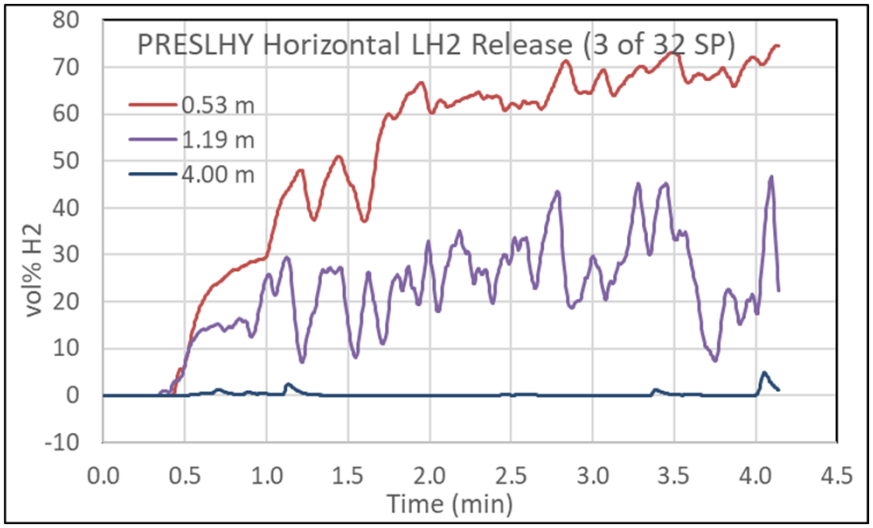
Role of Hydrogen Sensors
- Facility Safety (often mandated)
- Elucidation of released hydrogen behavior
- Verification of hydrogen purity (Fuel Quality)

Challenges (real and perceived)
"Hydrogen Sensors Don't Work"
- Not true but not totally untrue
  - Inaccurate manufacture's specification
  - Poor deployment strategy by end-users--safety should be designed into facilities and not just install.

Critical Gaps
- Lack of science-based deployment guidance
  - Complex hydrogen release behavior
- Expectations of performance
- Cost of ownership
- Smart integration in support of H2@Scale

Need to support CDO/SDO
- Pre-normative research
- Verification tools
- Document development

Installing the NREL HyWAM at HSL (in support of PRESLHY, March 2019)



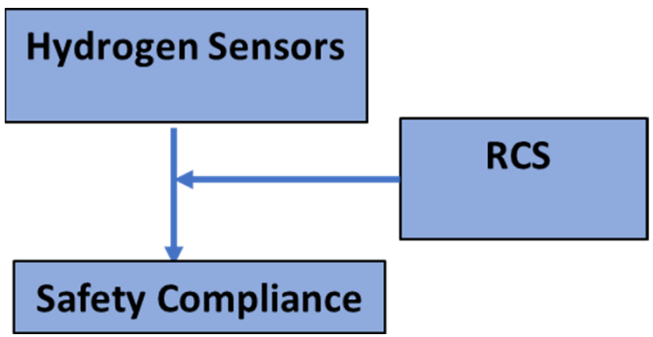
H_2 Measurements made with the NREL HyWAM at HSL in support of PRESLHY
(Pre-Normative Research for the Safe Use of Liquid Hydrogen)

Hydrogen Sensors represent a critical element in a facility safety system but must be reliable and properly deployed to be effective

Approach: Evolving mission for hydrogen sensors and the NREL H_2 Sensor Testing Laboratory—Sensors and Mitigation

Traditional Focus
(performance evaluation)

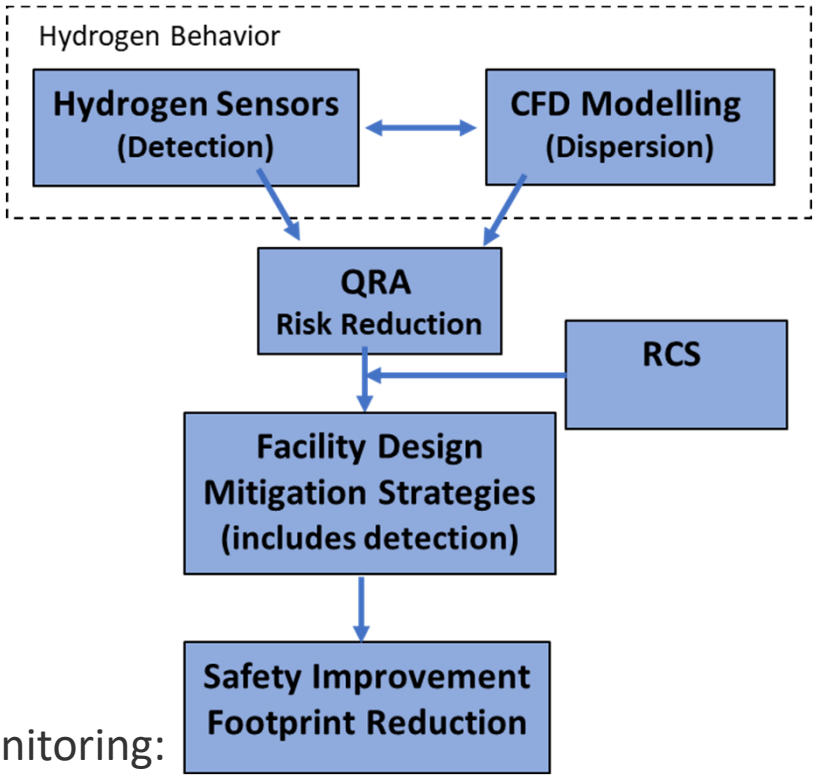
- Sensors provide critical safety factor
  - Provide warning before unsafe conditions
    - Activate Corrective Measures (ventilation)
    - Focus: metrological performance (RT, Range)



Assurance of Performance for General Safety Compliance

Emerging Focus
Integration into a risk mitigation strategy

- Temporal and spatial H_2 measurements
  - Tool for hydrogen behavior (validated CFD)
    - To integrate with QRA for facility design
    - Impacts safety and footprint



Active Monitoring:
One strategy for risk reduction

Active Monitoring is one of several strategies to achieve facility safety

Approach: Mission and Strategy of the NREL Sensor Testing Laboratory—Sensor Systems and Field Deployments

Sensor Performance Evaluations

- Remains a core capability but at a lower activity level
- Supports infrastructure and vehicle clients and applications
- Commercial and developing technologies

Field Deployments

- Infrastructure safety and implementation (HyWAM)
  - Indoor and outdoor case studies and deployments
  - Elucidation of release behavior—GH2 and LH2 safety research
  - Support behavior models development, QRA, and C&S.
- Vehicle Application
  - Verify safety regulation requirements (e.g., GTR)

Strategic partnerships to support HSR&D Mission

- IAGs, WFOs, NDAs, and sub-contracts
- Government agencies, industry, and research institutions
- National and International Partnerships
  - Support national and international initiatives (H2@Scale, PRESLHY, SHIFT, HyIndoor)
- Support C&S Development and Safety
  - Pre-normative research, verification methods, and document development

H_2 Sensor Testing Apparatus

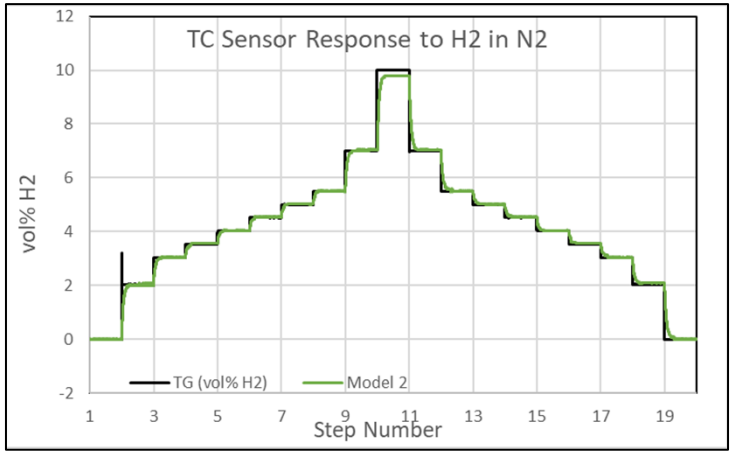
FCEV Exhaust Measurements at Environment Canada (July 2019)

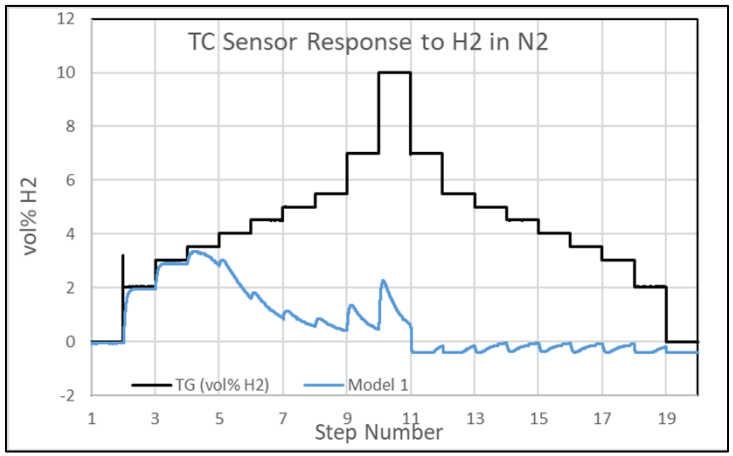
The NREL Sensor Laboratory supports Infrastructure Safety

Accomplishments and Progress: General Sensor Testing and Performance

Overview

- Sensor testing is a unique NREL capability
  - Utilizes specialized test apparatus of in-house design
  - Subjects sensors to controlled gas exposures and environments (T, P, RH, background gas composition)
  - Verification of sensor performance
- Support sensor developers and end users for both vehicle and Infrastructure applications
- Support NREL HSR&D projects
  - Qualification of sensors for HyWAM
  - Method development for the GTR
  - Exploratory advanced leak detection
    - Thin-film sensors with RFID interrogation (subcontract)
    - Alternative detection strategies (e.g., ultra-sonic) with industrial partner.





Not all sensors are equal

Performance evaluation for an end-user client (simultaneous testing of two sensor models)

Verification of sensor performance is critical to assure end-user confidence

Accomplishments and Progress:
General Sensor Testing and Performance
FCEV Exhaust Analyzer—Verification of GTR-13

GTR 13 Overview

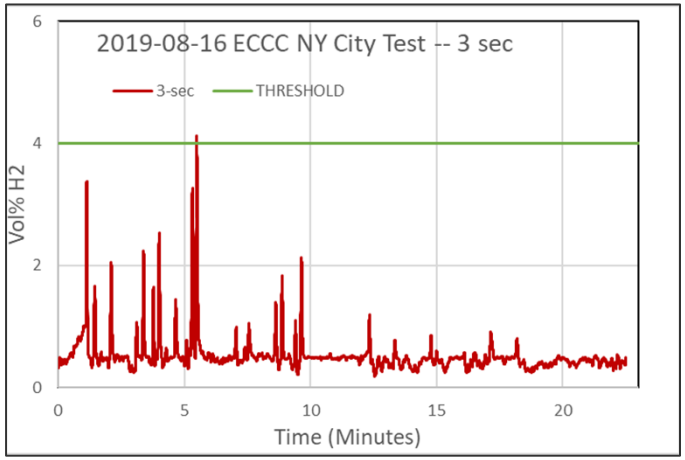
- Basis for the development of the FMVSS/CMVSS
- Prescribed FCEV H_2 exhaust level requirements (< 8 vol% at all time; <4 vol% over 3-sec moving average.)

NREL FCEV Exhaust Analyzer

- H_2 Detection Technology for GTR-13 verification
- On-going collaboration with Transport Canada and Environment and Climate Change Canada (ECCC).
- NREL Exhaust Analyzer tested on commercial FCEV at the ECCC Vehicle Emissions Testing Laboratory
  - Simulated urban and highway driving tests

NREL Exhaust Analyzer—deployment at ECCC

- Meets GTR Requirements (response time, range)
- Water mitigation strategies were partially but not completely successful
- NREL and ECCC (and Transport Canada) will maintain on-going collaborating for FCEV safety testing (GTR).
- Results presented at the 2019 International Conference on Hydrogen Safety (Adelaide, AU)



H_2 in FCEV exhaust as measured by the NREL Exhaust Analyzer at ECCC under simulated driving conditions (3-sec moving average of data as per GTR requirement)

Regulatory requirements need a means to verify compliance.
The NREL FCEV Exhaust Analyzer meets the GTR metrological requirements for compliance verification.

Accomplishments: Proposed NREL HyWAM Deployments and Development Activity

NREL HyWAM Deployment Strategies to Support LH2 Behavior R&D (Completed and Pending)

- NREL issued a Provisional Patent Prov 18-28
  - U.S. Application No. 62/948,896 "Hydrogen Wide Area Monitor" December 17, 2019.
  - Basis for TCF CRADA with KWJ Engineering to support HyWAM demonstration and commercial development
  - Research tool and basis for a commercial active monitoring system
- HSL/HSE (UK): Unignited releases, cold plume combustion behavior, and electrostatic discharge performed under PRESLHY (September – October 2019); NREL deployed a 32-point HyWAM under an HSL-NREL NDA
  - Expanded collaboration to hydrogen – Natural Gas blends (HyIndoor); activity is pending
- CGA-Chart Industries: Heat radiance of ignited cold plumes; collaboration performed under an NREL-CGA NDA (administratively delayed several times, most recently due to Covid 19; now scheduled for September 2020)
- SNL-LLNL dispersion of LH2 releases; collaboration performed under the auspices of respective AOP projects (administratively delayed due to Covid 19; schedule pending)
- Plug Power to deploy at a commercial facility with weekly deliveries, performed under an NDA (administratively delayed, in part, due to Covid 19); deployment is pending
- Exploring support of SH2IFT with Gexcon (Safe Hydrogen Fuel Handling and Use for Efficient Implementation); pending for August 2020 (potential WFO, under development)
- Exploring stand-off methods for leak detection to supplement or supplant gas sensors under an NREL technical service agreement with an industrial partner; (start date: April 2020)

The NREL HyWAM

- A research tool to support the development of Hydrogen behavior models
- Basis for an active monitoring safety system as part of a facility risk mitigation strategy
- One of several mitigation strategies to minimize risks with unintended H_2 releases.

Accomplishments: NREL HyWAM Deployment in Support of PRESLHY

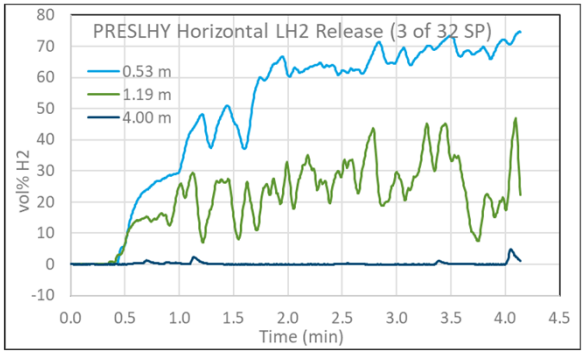
HSL/HSE PRESLHY Program
(Pre-Normative Research for the Safe Use of LH2)

- Multiple "tasks" on LH2 release behavior
- NREL provided a 32-point HyWAM System
  - Supported design review and operation
  - Site visit (March 2019) to install HyWAM for planned releases in April/May (delayed until September- November 2019 but were held!)
  - 3-dimensional sample points distribution down stream from horizontal release point
- Joint paper on HyWAM deployment at the 2019 ICHS (Adelaide, AU)
- Draft HSL report under review
  - Data & findings to be shared with H_2 community
- Preliminary summary presented by HSL (Simon Coldrick) to NFPA 2 Storage User group
- Expanding NREL-HSL collaboration (HyIndoor)

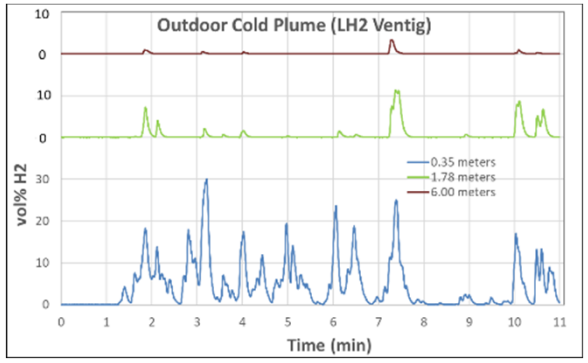
Hydrogen Wide Area Monitoring (HyWAM)

The quantitative spatial and temporal 3-dimensional profiling of hydrogen releases (planned and unintentional)

See: "Hydrogen Wide Area Monitoring of LH2 Releases" W. Buttner, J. Hall, P. Hooker, S. Coldrick, T. Wischmeyer, Proceedings of the 8th Int. Conf. on Hyd. Safety



H_2 profiles during horizontal release (calm day)—3 of 32 sample points



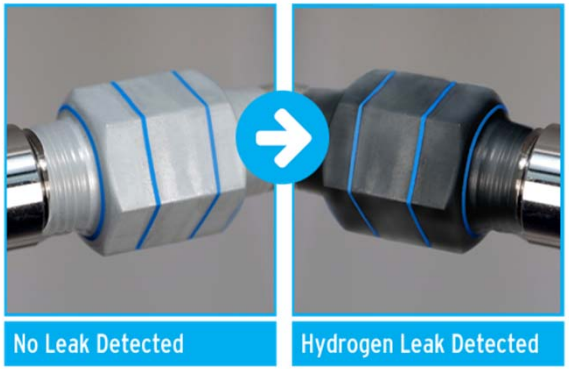
H_2 profiles during horizontal release (windy day--typical) –3 or 32 points

HyWAM support structure down-stream from the HSL LH2 release apparatus

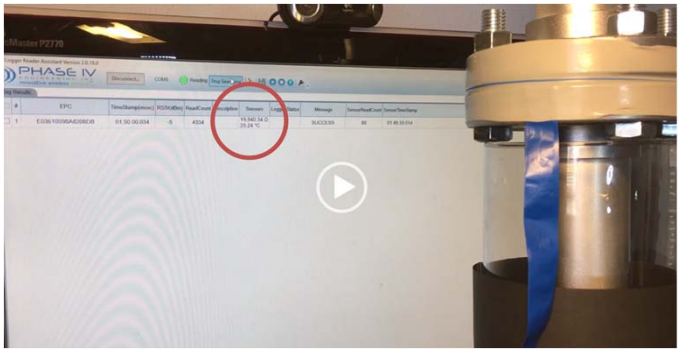
Accomplishments and Progress
Advanced Sensor Development
(supported by a NREL subcontract with Element One)

Innovative Thin-Film Sensors With RFID (Subcontract)

- Thin Film sensing elements with hydrogen-sensitive layers
  - Exposure to H_2 produces both a zero-power colorimetric (visual) response and an electronic signal with ultra-low power requirements for transduction and measurement.
- H_2-sensitive thin-films were configured into DetecTape® , a wrap applied to pneumatic components that serves as a passive H_2 leak indicator (a colorimetric response to H_2)
- Prototype DetecTape with RFID demonstrated; amenable for ultra-low power detection with remote interrogation capability
- Testing and evaluation on-going at NREL



Visual H_2 leak detection
Colorimetric detection of H_2 leaks with wrap ("DetecTape)



Remote Detection of H_2 Leak
H_2-sensitive wrap communicating to computer screen via RFID

H_2 leaks identified through remote interrogation with RIFD

Accomplishments and Progress: Internships within the NREL Sensor Laboratory

On-going mentoring of undergraduate scientists and engineers within the NREL Sensor Laboratory

Student Interns within the NREL Sensor Laboratory

- Mutually beneficial
- Real-world research experience in H_2 and alternative energy R&D
- Assigned as "technical lead" on a topical project
  - Interactions with clients
  - Allowed to present on their own work
  - Good publication record (co-authorship on talks, reports, AMR reviews, and journal articles)
- FY20 interns: Tashi Wischmeyer & David Pearman
- Successful post-graduation careers of past interns
  - Several have hired on at NREL (FTE & Consultants)

NREL Team (T. Wischmeyer* & W. Buttner) setting up HyWAM at HSL (March 2019)
* Intern UC Boulder

An NREL Internship provides real world experience in renewable energy.
Several Sensor Laboratory Interns have been hired by NREL

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

Overall the comments from the 2019 AMR were positive and recognized the importance and contributions of the NREL Sensor Testing to the DOE Hydrogen program. This project received an average score of 3.5.

Project Strengths:

- Bill Buttner is very clearly the right person for this project, as he has a real vested interest and seems to very much enjoy the work. There are some really good things that have come out of this project, along with other things that seem more like busy work. All in all, it is a strong project.

- This PI is very proud of the project's collaborations and coordination with entities outside of NREL, and he should be.

Reply: The PRESENTER choses to let the reviewer's comments speak for themselves.

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

Project Weaknesses:

- There is no question that this work has helped advance DOE goals for other projects where sensors are a key parameter for completion. However, this project primarily supports other projects, and this project does not have a clear objective as to what it is supposed to deliver. This is a gap, moving forward. This might be expected of any 10-year-old project.
- There is a lack of objective; the project needs an overall objective. Lacking an objective, the project is wandering and somewhat reactive. Perhaps those projects that request support should fund that support. There is also a loss of focus on new technology sensors. There seems to be less of a focus on the development of new types of sensors that otherwise improve upon the behavior of those that already exist. It is stated that sometimes sensors work, and sometimes they do not. It is not clear what is being done to directly improve that performance and perception. There is also a weakness in the HyWAM definition; this has exciting potential but needs better definition. There is a reference to "standoff" devices; this is the technology that could provide a breakthrough, but there is very limited information provided on this potential.

Reply: The recognition that the Sensor Laboratory has helped advance DOE goals is much appreciated. The suggestion that the lab has been reactive rather than proactive without a clear objective may be misleading. A key barrier in slide 2 "Safety is not always treated as a continuous process" regrettably reflects that safety is often an after-thought by the community. The sensor laboratory has always responded to the needs of the hydrogen community and does so by actively reaching out to key stakeholders (as exemplified by our extensive agreements and partnerships). But we remain cognizant of stakeholder's concerns. However, in some regards the comment is true, since the perception that "sensors don't work" had been very prevalent and still persists, even within NREL, and this attitude continually needs to be addressed. The above comments seems to question the role that detection plays for hydrogen safety. Current limitations are recognized and the NREL Sensor Laboratory has pursued creative and effective approaches for hydrogen detection within allotted budgets and resources. Presently we are actively pursuing non-traditional strategies for active monitoring, including the NREL HyWAM as well as standoff methods (e.g., ultrasonic) through strategic industrial partnerships. Also, through strategic collaborations, we are also endeavoring to quantify the impact of active monitoring on facility safety. These partnerships bring in resources for sensor laboratory activity that are not otherwise available within NREL.

Collaborations: Private and Government Partnerships

Performance & Qualification (Safety)

Sensing Element (Sensor) Development

- Element One, Inc. (subcontract, SBIR)
- Spec Sensor (SBIR)
- Panasonic (NDA)

Infrastructure Support/Safety

- AVT (subcontract),
- KWJ (TCF CRADA)
- First Element (TCF CRADA--informal)
- Shell North America (TSA)
- CGA/Chart, Inc. (NDA)
- ZCES (NDA)

Vehicle Support

- Ford Motor Company (NDA)
- GM (under an existing NREL-GM CRADA)

HyWAM Development and Deployments

- CRADA (Toyota)
- CGA/CHART (NDA)
- Shell (TSA)
- LLNL/SNL (AOP)
- HSL (NDA)
- Plug Power (NDA)

Process Monitoring and Methods

Infrastructure Support

- NFPA 2 H_2 Storage Safety Task Group
- ASTM D03 Fuel Quality Methods

Vehicle Support

- SAE Fuel Cell Standards Committee

Government Partnerships

- DOT/NHTSA with TCa/ECCCa
- HSL (LH2 behavior/HyWAM)
- CA-DOE Hydrogen Infrastructure Research Consortium (CRADA)
- LANL

The NREL Sensor Laboratory

A resource to the H_2 community

- **Infrastructure, vehicle, and new markets**
- **Sensor developers and end-users**
- **Active monitoring system to support R&D**
- **Formal and informal agreements**
- **Available for WFO**

Remaining Challenges and Barriers

Hydrogen Sensors for Safety Applications

- **Sensor Deployment Guidance:** Sensor placement strategies are often done by intuition or worse (e.g., without any apparent thought at all). Formalized guidance documents are lacking. A draft document was developed for indoor facilities through a subcontract with AVT; this guideline has not yet been fully vetted, which is part of ongoing activity.
- **Sensor Cost (capital and operational)**: Cost-effective sensor technology is necessary for large facilities (e.g., H_2@scale). These may include alternative detection strategies in addition to "point sensors" commonly used in small facilities.
- **Active Monitoring for Enhanced Safety/HyWAM**: An economical HyWAM with the necessary metrological characteristics does not exit, especially for routine use. This can support H2@Scale. Numerous deployment studies with key stakeholders were planned for FY20 to profile cold hydrogen plume behavior following LH2 releases; most were delayed due to "administrative" delays, including covid-19 shutdowns as well as LH2 availability for R&D activity.
- **Integration of Active Monitoring as a Risk Reduction Strategy:** QRA (e.g., via HyRAM) provides the tools to quantify risk reductions, but active monitoring requires hydrogen behavior models to guide placement for QRA. The integration of behavior models into HyRAM is not necessarily straight forward; this is being addressed with an ongoing partnership with AVT
- **Complex Standards Requirements**: Strategies for meeting safety requirements require complex testing and validation; standards and safety strategies are not internationally harmonized. Many instruments are not designed for Class I, Division 2 requirements and appropriate alternative means and methods are cumbersome and expensive.

Future work: The NREL HSR&D Program—Implementing a holistic approach to hydrogen safety and efficient use

Any proposed future work is subject to change based on funding levels.

AMR Presentation

NREL Hydrogen Sensor Testing Laboratory (SCS021; W. Buttner, M. Post, K. Hartmann, J. Thorson, M. Koleva, T. Wischmeyer, D. Pearman

- Sensor testing and performance testing
  - GTR support, client support, C&S development, and advanced sensor evaluation
- Hydrogen Wide Area Monitoring (HyWAM) (development and testing)

Other HSR&D AMR Presentations

Guidance for Indoor Sensor Placement (SCS027, Poster) A. Tchouvelev, W Buttner

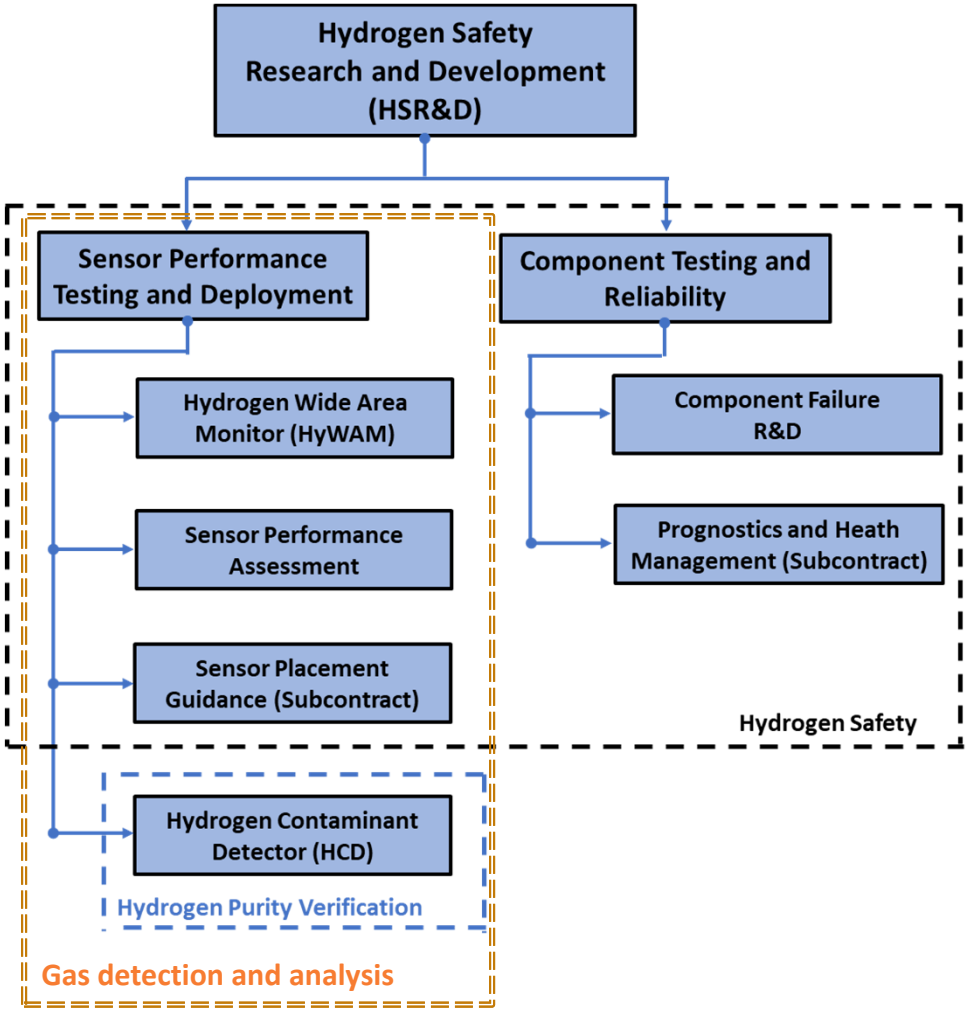
- Sensor placement plus integration of CFD & QRA strategies for indoor facility safety; expanding to outdoor

Component Failure R&D (SCS001, Poster) J. Thorson, K. Hartman, W. Buttner

- H_2 leak rate of failed components; PHM with UMD

Hydrogen Contaminant Detector (h2042; Poster) W. Buttner, M. Koleva, M. Post, K. Hartmann

- On-site, in-line FQ verification



Detection is part of a holistic approach to facility safety and efficient use of hydrogen and represents one element of HSR&D effort

Proposed Future Work: 1- and 5-Year Goals for the HSR&D

Any proposed future work is subject to change based on funding levels.

Activity	1 year	5 year
HyWAM	Characterize the dispersion of hydrogen in outdoor facilities and investigate advanced concepts.	Risk reduction quantification via active monitoring tools integrated with other mitigation strategies. Explore and demonstrate feasibilty of advanced concepts.
Sensor Placement	Dissemination guidance to RCS community	Outdoor partially confined/congested GH2 release analysis and provide guidance for risk mitiigation strategies (eg design, montitoring, etc) for compressed and liquid H2 installations as well as NG/H2 blends.
Component Reliability and Failure Mechanisms	Share the data and lessons learned from testing several failed components with industry	Integrate those data into hydrogen safety standards and QRA methods and models
Prognosis & Health Monitoring (PHM)	Preliminary design of algorithm for predictive risk modeling for component failure	Identification of potential changes to NFPA 2 or ISO 19880-1 regarding safety distances. Incorporate into QRA for LH2 storage
General Sensor Testing and Evaluation	Support industry and regulatory agencies with hydrogen sensor testing and input on deployment	Work with industry on novel concepts for hydrogen detection
Thin Film Sensors with RFID	Hydrogen sensors will continue to be optimized for mid- and large-scale infrastructure. Commercial partners will be identified for development and widespread deployment of automated hydrogen leak detection sensors.	Low-cost automated sensing networks will be deployed in hydrogen storage facilities, hydrogen fueling stations, and in fuel cell energy production locations for rapid leak detection.

Outcome of the DOE FCTO SCS subprogram 1-Year and 5-Year Planning Meeting (February 2020)

- Active Monitoring Identified as a critical safety strategy and a DOE resource
- Component R&D (failure frequency and impact) to support safe designs of H2 facilities

Technology Transfer Activities

- **NREL Provisional Patent** PROV/18-28 “Hydrogen Wide Area Monitor”, W. Buttner, (December 17, 2019) Application No. 62/948,896.
- Technology Commercialization Fund Project “Commercialization of the NREL Hydrogen Wide Area Monitor (HyWAM)” CRADA CRD-18-00784) with industrial partners (KWJ, First Element) to develop a effective HyWAM based upon NREL Provisional Patent 18-28

Summary

Relevance: Detection is recognized as a critical hydrogen safety element that facilitates the safe implementation of hydrogen infrastructure as both a tool to support H_2 behavior research and as an element in a deployed active monitoring safety system.

Approach: NREL Sensor Laboratory tests and verifies sensor performance for manufacturers, developers, end-users, regulatory agencies and SDOs/CDOs NREL deployment activity supports regulatory requirement verification and hydrogen behavior models.

Accomplishments and Progress: NREL's R&D accomplishments have supported developers, industry, and SDOs by providing independent third-party assessment of performance and sensor deployment expertise not otherwise available.

Collaborations: Collaboration with other laboratories (HSE/HSL, LANL, SNL, universities, private industry) has leveraged NREL's success in advancing hydrogen safety sensors and process control.

Proposed Future Work: NREL will support hydrogen deployment and the proper use of hydrogen sensors and other advance detection strategies. NREL will support the development of improved methods to verify fuel quality. NREL will continue to work with SDOs to maintain and update documents, when required.

Summary: Advancement from 2020 of on-going projects and activity

Project/Activity	FY 19 Advancements	FY 20 Advancements
SAE TIR J3089	Passed ballot and was published (https://saemobilus.sae.org/content/j3089_201810)	Activity Closed
HyWAM (Outdoor Applications)	On-site deployment of NREL HyWAM (GH2) internal to NREL, active collaboration to deploy during planned LH2 releases (HSL, CGA/Chart, LLNL/SNL). HyWAM test plan complete for HSL LH2 Release. Site visits to HSL, Chart, LLNL	Provisional patent awarded; HyWAM deployed within ESIF with wind speed and direction sensor (sporadic GH2 releaes); deployed at HSL (under PRESLHY) and proposed support of HyIndoor; planned to support CGA/CHART study of ignited cold plumes (delayed till Sept); SNL-LLNL dispersion modelling (delayed) with additional opportunities with SH2IFT
HyWAM (Indoor, GH2/He); Sensor Guidance	Empirical validation of CFD indoor release models by NREL HyWAM. Preliminary sensor placement and guidance document under development (2019 ICHS Paper)	Draft sensor placement guidance document developed and pending vetting. Integration of external hydrogen models into HyRAM for risk reductions. (see Poster SCS 027 "Guidance for Indoor Sensor Placement"). Expanding activity to partial confinement of outdoor releases. Internal NREL discussion with EHS group proposes using HyWAM for AICHE "Smart
FCEV Exhaust Analyzer, support of GTR 13	Under DOT guidance, worked with TC and ECCC. Revised probe design and tested on FCEV for compatibility with ECCC test facility. Field Test at TC/ECCC planned for 2019.	Analyzer successfully demonstrated on a FCEV under simulated driving conditions at ECCC. Design modifications for moisture management identified and are being implemented. Continued ECCC-NREL collaboration planned for FY20.
Sensor Testing and Evaluation	Performance evaluation remains a core capability of the NREL Sensor Lab, but more focused under NDAs and TSAs with sensor developers and end-users & support HyWAM.	Remains a core capability with continued support to hydrogen infrastructure and vehicle clients. Outreach to other industries (e.g. aerospace--NASA, Blue Horizons, and battery) on proper use of sensors.
CDO/SDO Committees	Continued participation on SAE standards committee (e.g., revised J2719--Fuel Quality); active on NFPA 2 Storage Task Group,	On-going active participation on SAE Fuel Cell Standards, NFPA 2 Hydrogen Storage Task Group, and ASTM working group on lighter than air fuels.; support of ISO TC 197
FQ Verification	Technical Lead on HCD Task within the auspices of a NREL-DOE-CA CRADA ; Provisional Patent on Interface and ROI of HCD analyzer	Demonstrated metrological performance of two HCDs. In process of installing HCDs into the NREL dispenser using an automated HCD to Dispenser interface (the HCD-I). (see Poster h2042 "On-Site, In-Line FQ Verification"
Component R&D		Developed the Leak Rate Quantitation Apparatus (LRQA) for quantifying hydrogen leak rates through failed high-pressure components. Subcontract with UMD (Prof. K. Groth) on advance reliability methods for hydrogen components. (see Poster SCS OO1 "Component Failure R&D)

Much of the NREL Sensor laboratory FY20 activity is ongoing and naturally builds off the past accomplishments

Thank You

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Publication Number

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Technical Back-Up Slides

(Include this “divider” slide if you are including back-up technical slides [maximum of five]. These back-up technical slides will be available for your presentation and will be included in Web PDF files released to the public.)

Publications and Presentations

Talks and Presentations

- "Hydrogen Wide Area Monitoring of LH2 Releases," William Buttner, Jonathan Hall, Phil Hooker, Simon Coldrick, Tashi Wischmeyer, presented at the 8th International Conference on Hydrogen Safety (September 24-26, 2019), Adelaide, Australia.
- "Compliance Measurements of Fuel Cell Electric Vehicle Exhaust," William Buttner, Aaron Loiselle-Lapointe, Tashi Wischmeyer, presented at the 8th International Conference on Hydrogen Safety (September 24-26, 2019), Adelaide, Australia.
- "Safety code equivalencies in hydrogen infrastructure deployment," Carl Rivkin, Crystal Xie, William Buttner, presented at the 8th International Conference on Hydrogen Safety (September 24-26, 2019), Adelaide, Australia.
- "Development of Risk Mitigation Guidance for Sensor Placement Inside Mechanically Ventilated Enclosures Phase 1," A.V. Tchouvelev, W. Buttner, D. Melideo, D. Baraldi, B. Angers, presented at the 8th International Conference on Hydrogen Safety (September 24-26, 2019), Adelaide, Australia.
- "NREL Hydrogen Sensor Testing Laboratory," William Buttner and Tashi Wischmeyer, DOE Hydrogen and Fuel Cells Program 2019 Annual Merit Review and Peer Evaluation Meeting (April 29 – May 1, 2019), Washington, DC.
- "NREL Hydrogen Sensor Testing Laboratory" William Buttner, Tashi Wischmeyer, Matthew Post, Jacob Thorson, Kevin Hartmann, Codes and Standards Tech Team Webinar (September 19, 2019).
- "Update on Hydrogen Wide Area Monitoring (Active Monitoring as a Mitigation Strategy for LH2 Setbacks)" W. Buttner and T. Wischmeyer, Presented at the NFPA 2 Hydrogen Storage Task Group, (October 23-24, 2018), Albuquerque, NM
- "Use of Hydrogen Sensors in Active Monitoring for Hydrogen Facility Risk Reduction" William Buttner, Tashi Wischmeyer, Matthew Post, Jacob Thorson, Presented at the AICHE 2019 Conference on Hydrogen Safety, Sacramento, CA (October 14-15, 2019).
- "On-Site, Near Real-Time Analysis of Critical Impurities in Hydrogen" Mariya Koleva, William Buttner, Matthew Post, Jennifer Kurtz, Fuel Cell Seminar, Long Beach CA (November 5 -7, 2019)
- Component Failure R&D, Jacob Thorson, Kevin Harmann, William Buttner, Katrina Groth, Camilla Jullian presented to the CSTT (May 14)
- "California-DOE Hydrogen Research Consortium--The NREL In-Line Hydrogen Contaminant Detector Project" William Buttner Mariya Koleva, Matthew Post, Kevin Hartman, Presented to the H2@Scale Working Group Webinar (May 19, 2020)

Publications and Presentations

Publications—Conference Proceedings

- “Hydrogen Wide Area Monitoring of LH2 Releases,” William Buttner, Jonathan Hall, Phil Hooker, Simon Coldrick, Tashi Wischmeyer, Proceedings of the 8th International Conference on Hydrogen Safety (September 24-26, 2019), Adelaide, Australia.
- “Compliance Measurements of Fuel Cell Electric Vehicle Exhaust,” William Buttner, Aaron Loiselle-Lapointe, Tashi Wischmeyer, Proceedings of the 8th International Conference on Hydrogen Safety (September 24-26, 2019), Adelaide, Australia.
- "Safety code equivalencies in hydrogen infrastructure deployment," Carl Rivkin, Crystal Xie, William Buttner, Proceedings of the 8th International Conference on Hydrogen Safety (September 24-26, 2019), Adelaide, Australia.
- “Development of Risk Mitigation Guidance for Sensor Placement Inside Mechanically Ventilated Enclosures Phase 1,” A.V. Tchouvelev, W. Buttner, D. Melideo, D. Baraldi, B. Angers, Proceedings of the 8th International Conference on Hydrogen Safety (September 24-26, 2019), Adelaide, Australia.

Publications—Journal Articles and Formal Reports

- Development of Risk Mitigation Guidance for Sensor Placement Inside Mechanically Ventilated Enclosures – Phase 1, A.V. Tchouvelev, W. Buttner, D. Melideo, D. Baraldi, B. Angers, International Journal of Hydrogen Energy (accepted, undergoing revision)
- “NREL Hydrogen Sensor Testing Laboratory”, W. Buttner, M. Post, J. Thorson, T. Wischmeyer, M. Koleva DOE Annual Progress Report (November 2019)
- “Characterization of a Selective, Zero Power Sensor for Distributed Sensing of H2 in Energy Applications” T. Wischmeyer, J. R. Stetter , W. Buttner, V. Patel, D. Peaslee, International Journal of Hydrogen Energy (submission pending).